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RESEARCH MEMORANDUM

AN INVESTIGATION AT MACH NUMBERS 2.98 AND 2.18 OF AXIALLY SYMMETRIC FREE-JET DIFFUSION WITH A RAM-JET ENGINE

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NATIONAL ADVISORY COMMITTEE
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AN INVESTIGATION AT MACH NUMBERS 2.98 AND 2.18 OF AXIALLY SYMMETRIC FREE-JET DIFFUSION WITH A RAM-JET ENGINE

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SUMMARY

An investigation was conducted to determine the feasibility of using a supersonic free jet as a means of testing large air-breathing engines. An axially symmetric free-jet diffuser was investigated at a Mach number of 2.98 using ratios of jet-nozzle to engine-inlet area of 1.85 and 1.35 and at a Mach number of 2.18 using a ratio of jet-nozzle to engine-inlet area of 1.35.

A minimum operating pressure ratio of 5.5 was obtained at a Mach number of 2.98 with a ratio of jet-nozzle to engine-inlet area of 1.85. The total-pressure ratio of the flow through the jet diffuser was approximately equal to the over-all pressure ratio of the combined flow through the free-jet diffuser and engine and remained independent of the engine pressure recovery. In general, increasing the amount of high-kinetic-energy air passing around the engine and through the free-jet diffusers decreased the required starting and operating pressure ratios for the system regardless of whether the flow diversion was accomplished by decreasing the engine size or by increasing the engine-inlet flow spillage. For the normal-shock inlet, however, steady-state subcritical flow spillage reduced only the operating pressure ratio. Irrespective of the pressure ratios required for starting and operating, a ratio of free-jet to engine-inlet area of 1.35 was considered the smallest feasible because the engine-inlet lip was at the edge of the nozzle boundary layer.

A range of steady subcritical inlet operation was possible; the exact mass flow which could be spilled depended on the particular installation. Unsteady subcritical operation did not yield reliable quantitative measurements as related to free-flight conditions, except perhaps the value of engine mass-flow ratio at which buzz begins.

INTRODUCTION

An investigation was conducted at the NACA Lewis laboratory to determine the feasibility of using a supersonic free jet as a test facility for jet-propulsion engines in the Mach number range between 2.0 and 3.0.

Although this technique has been investigated and used in numerous facilities in this country and abroad (references 1 and 2), most of the installations were designed for and used with relatively small aerodynamic models obstructing the stream flow. In the present investigation, it was desired to determine whether a large engine filling at least half of the free-jet area could be practicably tested. Of prime importance in the investigation was the determination of the effectiveness of the annular free-jet diffuser in reducing the starting and operating pressure ratio of the free-jet system for various ratios of free-jet to engine-inlet area. 2398

In this respect, it was necessary to obtain quantitative data regarding the second-throat areas required for effective diffusion and to determine whether subcritical operation of the engine inlet was possible with the relatively large engine sizes contemplated. In addition, establishment of the interactions existing between the free jet and engine diffusion systems and determination of optimum engine-inlet locations for starting and operating were desired.

In the present investigation, several practical restrictions were imposed on the design of the annular free-jet diffuser because of existing local installations. These restrictions, some of which differentiate the present study from those of references 3 and 4, were:

(1) The diffusion length (supersonic and subsonic) was limited to approximately three engine-inlet diameters to allow ready accessibility to the engine components and accessories.

(2) The diffusion was started downstream of the engine-inlet lip so that an open light path would be available for schlieren or shadowgraph observations of the shock configurations in the region of the engine-inlet lip.

(3) The facility should be capable of testing inlets with lips inclined at least 20° to the free-stream air.

(4) The annular free-jet diffuser should be capable of maintaining suitable engine test conditions when the flow from both the annular free-jet diffuser and the engine are recombined and exhausted through a single air-induction system.

In reference 3, the ram-jet test vehicle created a minimum of disturbance in the external flow around the engine and the diffusion was extended over the entire engine length. In reference 4, diffusion of the external flow was initiated upstream of the engine-inlet lip.

NOTATIONS AND SYMBOLS

The notations and symbols used are as follows (see also figs. 1 to 3):

A	area
f	frequency (cps)
x	axial distance from plane of jet-nozzle exit to engine-inlet lip
x_β	axial distance from plane of jet-nozzle exit to intersection of Mach line from jet-nozzle lip with axial projection of inlet lip
M	Mach number
P	stagnation pressure
p	static pressure
r_i	engine-inlet radius (2.5 in.)
β	Mach angle, $\sin^{-1} 1/M$
θ	angle between axis of engine and line joining cone apex with engine-inlet lip (deg)

Subscripts:

0	nozzle entrance
1	jet-nozzle exit
2	minimum area (throat) of free-jet diffuser
3	exit of free-jet diffuser
c	exit of engine diffuser or entrance of engine combustion chamber
e	engine exit
i	engine inlet without centerbody
m	minimum area between engine lip and centerbody surface
p	plenum surrounding free jet
t	tunnel diffuser (location of pitot rake measuring pressure of combined flow through annular free-jet diffuser and engine)

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EXPERIMENTAL MODELS AND INSTRUMENTATION

The investigation was conducted with an axially symmetric model utilizing an 8-inch ram-jet engine as a representative test body. Although the jet diffuser was designed to provide a clear light path through the region about the engine lip, schlieren apparatus could not be used without major structural alterations to the facilities. Consequently, the investigation was supplemented by runs with a smaller two-dimensional nozzle and engine employing a schlieren system for flow observation. 2398

Axially Symmetric Model

The axially symmetric free-jet diffuser was of the annular convergent-divergent type with a well-rounded intake to collect the flow gradually into the throat. The flow was diffused radially (in a direction fixed by the external engine-lip angle) as well as axially to obtain a maximum variation in second-throat area for a given displacement of the diffuser and to shorten the axial diffusion length. A schematic diagram of the experimental model is presented in figure 1. The 20-inch supersonic wind tunnel was converted to a free jet by inserting an axially symmetric wooden nozzle into the test section. The 8-inch ram-jet engine with a 5-inch inlet diameter and 20° half-angle cone, which was used as the representative test body, is also shown. The engine was originally designed for a Mach number of 1.87 and used in reference 5. Modifications to the engine included a change in cone-tip projection to position the oblique shock in the vicinity of the engine lip at a Mach number of 2.98, the removal of the flame holder and fuel injectors from the combustion chamber, and the removal of the cone and centerbody to obtain a normal-shock inlet when desired.

The cone-tip projections in terms of the angle θ between the axis of the engine and a line joining the cone apex and the engine-inlet lip were 29° and 31.2° for a Mach number of 2.98, and 38.6° for a Mach number of 2.18. For these cone-tip positions there was no internal contraction of the engine diffuser.

Two nozzle sizes, defined by the ratio of nozzle-exit area to engine-inlet area A_1/A_i, of 1.85 and 1.35, respectively, were investigated at a Mach number of 2.98. At a Mach number of 2.18 only the 1.35 nozzle was considered.. All nozzles were designed by the method of characteristics and a boundary-layer correction was incorporated. The theoretical design Mach numbers based on one-dimensional area ratios were 3.04 and 2.21.

The free-jet annular diffuser consisted of two pieces (see fig. 2). A conically diverging sheet-metal shroud was faired into the engine lip to form the inner contour. A wooden cylinder was cut to form the outer contour. This outer contour could be moved axially while the free jet was in operation. The free-jet plenum was sealed with inflatable tubing against air leakage.

The instrumentation used to measure steady-state flow pressures was located as follows (see fig. 1):

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(1) A static orifice in the top and bottom surfaces of the nozzles approximately 1/2 inch upstream of the exit lip (station 1)

(2) A static orifice in the bottom of the jet plenum (station p)

(3) A five-tube pitot rake at the exit of the free-jet diffuser (station 3)

(4) Two five-tube pitot-static rakes at the entrance to the engine combustion chamber (station c)

(5) A five-tube pitot rake at the end of the tunnel diffuser (station t)

All rakes were designed so that the tubes were located at the centroids of equal areas. Pressures were read on a multiple-tube mercury manometer and photographically recorded.

Pressures during unsteady or pulsing flow (buzz) were measured with an instantaneous pressure pickup having a range of ± 10 pounds per square inch and recorded with a strain analyzer and double-arm-pen motor recorder. The pressure pickups were of a type which utilized strain gages mounted on a diaphragm. One pickup was located at the free-jet plenum and the other, at the entrance to the engine combustion chamber. Both pressure pickups were referenced to their respective static-pressure orifices through suitable lengths of tubing that damped out the pressure fluctuations. The pressures thus recorded were the deviations of the instantaneous pressures from the dampened mean pressure.

Two-Dimensional Model

The apparatus used for the two-dimensional schlieren flow observation is shown schematically in figure 3. The tunnel width was 4 inches and the nozzle size was 1.35. The straight 20° external surface of the engine was used with both diffuser contours shown in figure 4 and formed the internal contour of the jet-diffuser flow channel. Diffuser contour A had a well-rounded air intake which simulated the three-dimensional model in that the flow was collected gradually at a point downstream of the intersection of the oblique shock, generated by the 20° engine lip, and the free-jet boundary. Contour B had a relatively sharp intake and captured the flow upstream of the intersection of the engine shock with the free-jet boundary.

The flow was observed with a two-mirror schlieren system. Pressure instrumentation consisted of a static orifice in each nozzle block 1/2 inch upstream of the exit, a static orifice in each plenum immediately downstream of the nozzle exit, and a static orifice in the 10-inch exit pipe. The velocity of the flow in the 10-inch pipe was low enough for the static pressure to be considered approximately equal to the total pressure.

For all runs, air was supplied to the jet-nozzle entrance at a stagnation temperature of 60° to 80° F and at a dew point of -20° to 10° F. Several check runs indicated that condensation did not affect starting or running pressure ratios appreciably if the dew point was held below 15° F. 2398

DISCUSSION OF RESULTS

The results of the present investigation are discussed in two parts: the first deals with the requirements for efficient supersonic operation of the free jet, and the second deals with the special requirements for suitable engine experimental conditions.

Free-Jet Considerations

Throughout the course of the investigation the over-all pressure ratio P_0/P_t remained approximately equal to the jet pressure ratio P_0/P_3, as illustrated in figure 5 for the two nozzle sizes of 1.85 and 1.35 operating at a Mach number of 2.98. The data were taken from several engine-inlet configurations. The increase in over-all pressure ratio above that of the jet pressure ratio for the 1.85 nozzle at an over-all pressure ratio greater than 9 can be attributed to the flow losses occurring between the jet-diffuser exit and the measuring station t in the tunnel diffuser. Below over-all pressure ratios of 9.0 and 12 for the 1.85 and 1.35 nozzles, respectively, the flow losses are minimized as a result of reduced jet-diffuser air velocities.

In addition, both the over-all total-pressure ratio and the diffusion ratio P_3/P_t remained independent of the engine pressure recovery P_c/P_0. In figure 6, a typical variation of the diffusion ratio with engine pressure recovery is shown. The diffusion ratio remained constant at an average value of approximately 1.008 over a range of supercritical engine pressure recoveries of 0.25 to 0.38. The slight variation of ± 0.004 in the diffusion ratio is within the experimental precision of pressure measurements.

Thus the over-all pressure ratio required for operation will be governed by the jet diffusion. This indication is probably a result of the geometry of both the air system and the engine in the vicinity of the engine exit. Although no such experiments were made in this investigation, it may be possible through suitable designs to utilize the potentially better diffusion of the engine as an ejector to aid the free-jet diffusion.

The significant trends in the over-all pressure ratio P_0/P_t required to start and operate the various free-jet nozzles over a wide range of cold engine operating conditions are exemplified by the data presented in
2398 figure 7. A normal-shock engine-inlet configuration was used to insure steady subcritical engine flow. The optimum contraction ratio $(A_1-A_i)/A_2$ as determined with supercritical engine-inlet operation was used to obtain the lowest operating over-all pressure ratio for the configuration. For convenience in determining the critical engine-inlet flow conditions, the engine pressure recovery P_c/P_0 is plotted in figure 7(a).

Over the entire range of engine operating conditions investigated, the over-all pressure ratio P_0/P_t required to start was always greater than that necessary for operation (fig. 7(b)). This phenomenon was encountered for most configurations tested and the quantitative results for other configurations and operating parameters are presented subsequently. The fact that the over-all starting pressure ratio is larger than that required for operation is attributed to recognized discontinuities associated with a swallowing of the shock which are analogous to those occurring in the pressure recovery of supersonic convergent-divergent diffusers.

In figure 7(b) the over-all starting pressure ratios show little change for supercritical ratios of engine outlet-inlet area but increase rapidly in the subcritical range. The required over-all operating pressure ratios remained constant in the supercritical range but in every instance were substantially reduced in the first portion of the subcritical range (ratios of engine outlet-inlet area less than 0.74). This beneficial effect was limited, however, and there existed a ratio of engine outlet-inlet area below which operation of the free jet could not be maintained. It should be noted that the jet-diffuser contraction ratio $(A_1-A_i)/A_2$ is based on geometric areas and that engine flow spillage ordinarily increases the effective contraction ratio of the flow and thus reduces the operating pressure ratio. However, as will be shown subsequently, the reduction in operating pressure ratio could not be attained through an increase in geometric contraction ratio with no flow spillage.

Other factors which influence the required over-all starting and operating pressure ratios are the jet-diffuser contraction ratio $(A_1-A_i)/A_2$ and the engine-lip position x/x_β. Typical results are presented in figure 8 for three engine-lip positions. The data indicate that the starting and operating pressure ratios are relatively insensitive to the contraction ratio in the vicinity of the minimum over-all pressure ratios and that for a given engine-lip position one fixed value of the contraction ratio is approximately optimum for both starting and operating. Also, the decrease in operating pressure ratio with contraction ratio is limited and the lowest operating pressure ratio does not occur at the highest value of the contraction ratio.

The minimum over-all starting and operating pressure ratios for all the configurations and Mach numbers investigated are presented in figure 9. The data are for engine-outlet areas corresponding to supercritical engine-inlet flow conditions during operation. In all cases both the over-all starting and operating pressure ratios decreased as the engine inlet was moved toward the jet. In addition, there was a beneficial effect on the over-all starting and operating pressure ratios of increasing the relative proportion of high- to low-kinetic-energy air flow around the engine and through the jet diffuser. This effect is shown by the reduction in over-all pressure ratios both as the nozzle size is increased from 1.35 to 1.85 and as the supercritical flow spillage around the engine is increased at a fixed nozzle size (by changing the 40° cone-tip position θ from 31.2° to 29°; for the cone position θ of 29°, the minimum engine-inlet area A_m for the starting condition was decreased by approximately 10 percent from the value for the cone position of 31.2°. For the operating condition, the oblique shock was ahead of the engine-inlet lip and spilled approximately 10 percent of the mass flow in the stream tube area A_i into the jet diffuser and also reduced the stagnation-pressure loss in the flow around the engine by accomplishing the required 20° deflection of the flow with two oblique shocks instead of one.)

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The effect of flow spillage around the engine is further illustrated at a Mach number of 2.98 with the 1.85 nozzle by a comparison of data between the normal shock and the 40° cone inlet with a tip projection of 31.2° (fig. 9(a)). For the operating condition, both inlets capture the same amount of mass flow and the minimum over-all pressure ratios corresponded closely to each other. For the starting condition, the minimum engine-inlet area of the 40° cone configuration, which is only 62 percent of the normal-shock inlet area (where $A_m = A_i$), forces more air around the engine and a marked difference in over-all pressure ratio is noticeable. With the 1.35 nozzle (fig. 9(b)), this relation is not so evident.

Engine-Operation Considerations

Suitable engine-operation conditions require that the stream flow into the engine inlet be free of shocks or expansions. The principal factor which can originate shocks or expansions in the free-stream flow

from an otherwise satisfactory nozzle is the pressure p_p in the plenum surrounding the free jet. A typical variation of the plenum pressure with the over-all pressure ratio is presented in figure 10 for various second-throat contraction ratios. The plenum pressure is expressed as the ratio of plenum to free-jet static pressure p_p/p_1. At the lowest value of the contraction ratio $((A_1-A_i)/A_2 = 0.428)$ the continuous rise in plenum pressure with decrease in over-all pressure ratio suggests a pressure feedback through the throat of the jet diffuser. Increasing
2398 the contraction ratio reduces this effect, but the level at which the plenum pressure remains independent of the over-all pressure ratio is increased. The increase in plenum pressure with contraction ratio for high values of the over-all pressure ratio again indicates a pressure feedback effect possibly as a result of the increase in the diffusion of the flow in the contracting region of the jet diffuser. In either case, the lowest over-all pressure ratios desirable on the basis of operation occur at values of the plenum pressure ratio considerably above 1.0, and strong shocks from the lip of the jet nozzle may affect the engine-inlet flow.

The strong shocks originating at the lip of the jet nozzle with increasing values of the plenum pressure and the potential detrimental effect on the engine-inlet flow may be seen in the schlieren photographs of the two-dimensional model shown in figure 11. As the contraction ratio was increased from 0.795 to 1.092, the plenum pressure rose from 1.408 to 1.709, and a contraction of the free-jet stream tube may be seen. At a plenum pressure of 1.709 (fig. 11(d)), the interaction between the oblique shock from the jet-nozzle lip and external surface of the engine cowl produced a strong shock at the engine-inlet lip. For this condition the engine inlet is no longer operating at free-stream conditions although the oblique shock from the nozzle lip appears to be downstream of the engine-inlet lip. Even the highest value of plenum-pressure ratio is considerably below the static-pressure ratio of 3.85 across the oblique shock generated by the engine lip.

For the three-dimensional investigation the maximum values of the plenum pressure at which free-stream engine-inlet flow conditions could be obtained were determined from curves similar to those of figure 12. With the ratio of engine outlet-inlet area held fixed at a supercritical value, the plenum pressure was varied by changing the contraction ratio and over-all pressure ratio over a range of values. Changes in engine pressure recovery for a given configuration and inlet-lip position x/x_β occur only when the plenum pressure rises high enough that compression waves influence the engine-inlet flow or the over-all pressure ratio decreases enough that the engine outlet is no longer choked.

In figure 12(a), the maximum plenum pressure which can be attained without influencing the engine-inlet flow is approximately 1.65 to 1.70

as may be seen for the contraction ratios of 0.428 and 0.501. The displacement of the two curves is a result of the slight change in engine-area ratio from 0.698 to 0.685. The change in trend of pressure recovery with plenum pressure between a contraction ratio of 0.501 and 0.637 (fig. 12(a)) is due to a decrease in the over-all pressure ratio below 6.8, the minimum value at which the engine outlet remains choked in this case (fig. 12(b)). Within the limits of experimental precision, a plenum pressure of 2.3 for a contraction ratio of 0.772 gave the same pressure recovery of approximately 0.305 as at the contraction ratio of 0.428. 2398

The lowest over-all pressure ratio at which the engine outlet will no longer choke will change, of course, with engine pressure recovery. Free-jet operation below this lowest pressure ratio does not necessarily have to be avoided, as corrections to engine data can be made if adequate pressure instrumentation is provided. Disturbances at the engine inlet must be avoided, however, if free-stream flow is to be simulated.

The experimental values of plenum pressure p_p/p_1 required to avoid disturbances at the engine inlet are presented in figure 13 for the configurations investigated. The increase in permissible plenum pressure with decrease in engine-inlet-lip position clearly indicates that the effects of the plenum pressure on the engine-inlet flow may be minimized by moving the engine inlet closer to the plane of the nozzle exit. However, the experimental values are much less than the theoretical ones obtained by using two-dimensional oblique-shock relations to calculate the engine-lip position x/x_β from the plenum pressure. Shock detachment at the engine lip such as previously shown in figure 11(d) and pressure feedback through the nozzle boundary layer which alters the displacement thickness within the nozzle in a manner initiating compression waves upstream of the nozzle exit can easily account for the discrepancy between experiment and theory. In general, the quantitative experimental values of plenum pressure are only approximate, because in some instances (particularly at an engine-lip position of zero) the change in pressure recovery with increasing plenum pressure was very gradual. However, the values presented are considered conservative.

The over-all pressure ratios required for suitable engine-inlet flows are presented in figure 14. The required pressure ratios for starting from figure 9 are shown for comparison. For the 1.35 nozzle, the over-all pressure ratios required for suitable engine operation conditions exceed those required for starting except in the vicinity of engine-lip positions of approximately zero (fig. 14(b)). This behavior is in contrast to the results of figure 9 which did not consider engine-inlet conditions in determining an operating pressure ratio. For the larger nozzle size of 1.85, the pressure ratios required for testing were approximately the same as the operating pressure ratios described in figure 9.

Irrespective of the pressure ratios required for starting and suitable engine operation, a pitot-static survey of the flow in the plane of the jet-nozzle exit showed that any appreciable decrease in nozzle size below 1.35 would result in the flow of the nozzle boundary layer into the engine inlet.

The minimum over-all pressure ratio of 5.5 attained at a Mach number of 2.98 for the 1.85 nozzle and an engine-lip position of zero is not
2398 judged unduly high upon consideration that 20 percent of the stagnation pressure P_1 of the bypassed air is lost through the oblique shock generated by the engine lip and that the associated compression of the flow is partially cancelled by subsequent expansion. In fact, the over-all pressure ratio of 5.5 measured herein as compared with that of approximately 4.4 obtained in reference 3 at the same Mach number and nozzle size may be accounted for by the difference in oblique-shock losses of the respective inlets and indicates that larger engine-inlet-lip angles may require correspondingly higher pressure ratios for operation. No correlation was possible, however, at the nozzle size of 1.35. The effectiveness of a free-jet diffuser in reducing the over-all pressure ratio required for suitable engine operation was exemplified by runs in which a pressure ratio of 15 was required when no diffuser or engine shroud was used. As another comparison, it may be estimated from a compilation of published and unpublished data that at a Mach number of 3.0, a closed tunnel with no model will require an over-all pressure ratio of 4.4 for operation. If a variable-geometry second throat is used, this pressure ratio is estimated at 3.2.

The jet-diffuser contraction ratios $(A_1-A_1)/A_2$ at which the over-all pressure ratios required for suitable engine operation were obtained are presented in figure 15. For engine-lip positions up to approximately 0.5 the over-all pressure ratios could be obtained within 3 percent with approximately 10 percent variation in the contraction ratio from the values shown.

Steady subcritical operation of the normal-shock inlet was obtained over a range of ratios of engine outlet-inlet area for all variations of Mach numbers, nozzle sizes, and engine-lip positions investigated. The steady-state flow into the engine inlet was not terminated by shock oscillation but rather, by a complete breakdown of the supersonic flow from the nozzle.

For the 40° cone inlet only a slight range of stable subcritical engine operation immediately following the critical point was detectable. Shock oscillation (buzz) then occurred, and the frequency increased as the engine outlet was closed. In figure 16, the frequency of the shock oscillation as a function of the ratio of engine outlet-inlet area is shown at a Mach number of 2.18 for the 1.35 nozzle at several values of over-all pressure ratio and contraction ratio. Although some scatter of the data occurred, notably at ratios of engine outlet-inlet area of approximately 0.58 and 0.61, the frequency of shock oscillation remained relatively constant over a range of over-all pressure and contraction ratios for a given ratio of engine outlet-inlet area. The limiting over-all pressure ratio at which the pulsations could be sustained was close to that required for starting. Although subcritical engine pulsing was encountered at all engine-lip positions investigated with the 1.85 nozzle, choking of the jet-nozzle flow prevented subcritical engine operation for the 1.35 nozzle at both Mach numbers investigated when the engine-lip position was zero. 2398

The experimental results presented in figure 16 did not correlate with theoretical calculations (dashed curve) made using the method presented in reference 6. Because good agreement was found between theory and experiments in other wind-tunnel runs in reference 6, it is felt that the large discrepancy between experimental and theoretical results of about 16 cycles per second in the vicinity of a ratio of engine outlet-inlet area of 0.66 indicates a considerable modulation of the frequency by the interaction of oscillating shock with the free-jet boundary and nozzle walls. The quantitative frequency data would therefore be unreliable, but qualitatively the data may be indicative as to whether or not shock oscillations would occur in free flight at the same Reynolds number.

The variation of pressure pulsations with time is presented in figure 17 for three ratios of the engine outlet-inlet area at a Mach number of 2.18 and a nozzle size of 1.35. The pressure fluctuation represents the deviation of the instantaneous pressure from that of the damped mean pressure. In figure 17 it can be noted that a close relation exists between the engine- and plenum-pressure fluctuations. The frequencies are the same and at a ratio of engine outlet-inlet area of 0.668, large amplitudes of engine and plenum pressures occur simultaneously. The shape of the engine wave form is very similar to that shown in reference 5. The wave form in reference 5 was obtained at a Mach number of 1.87 in a closed supersonic tunnel with the same engine inlet; the quantitative values are not reliable, however, because the extent of shock travel was far enough upstream to affect the nozzle-wall static pressures, and hence the flow into the engine inlet would be distorted by shock reflections from either the nozzle walls or the jet boundary.

Possible Improvements in Diffuser Design

The large rise in plenum-pressure ratio with increasing contraction ratio and decreasing over-all pressure ratio (figs. 10 and 11), which is associated with an annular diffuser with gradual intake, may be avoided in a diffuser with a rapid intake such as that represented by the two-dimensional diffuser of contour B, which is a type similar to that investigated in reference 4. Schlieren photographs of the flow about this type of configuration are shown in figure 18. In contrast to diffuser A (fig. 11), diffuser B allowed only a slight variation of 0.90 to 1.19 in the plenum-pressure ratio with an over-all pressure ratio change from 13.8 to 7.22. The variation in plenum-pressure ratio with contraction ratio was negligible.

2398 In figure 18, the contraction ratio of 1.239 was the maximum attainable. The leading edge of the diffuser is very close to the leading edge of the engine-inlet lip, and in a three-dimensional model the amount of flow observation would be limited. In figures 18(a) and 18(b) two regions of flow separation occur. The first region is immediately behind the nose of the contour intake; the second region is on the external surface of the simulated normal-shock inlet. In figures 18(c) and 18(d) the flow separation from the engine surface has shifted to the contour surface and the separation has moved upstream to the diffuser throat, which permits a possible pressure feedback into the plenum. The severity of this flow separation is due in part to the large angular divergence (31°) of the contour from the axial direction and the high pressure gradient induced by the 11° expanding flow channel. A more gradual expansion of the channel would therefore be desirable, although the diffuser-exit Mach number might be increased. Because the flow over the surface of the engine exterior begins with no initial boundary layer and that along the diffuser contour is subject to the turbulence created between the jet and the plenum, it is indicated that some turning of the flow towards the axial direction about the engine cowling would be desirable to reduce the curvature of the outer diffuser.

SUMMARY OF RESULTS

In an investigation to determine the feasibility of using a supersonic free jet as a means of testing large air-breathing engines, it was found possible to effectively utilize a convergent-divergent free-jet diffuser to reduce the over-all pressure ratio required to start, operate, and produce suitable experimental conditions in the free jet. The following results were obtained:

1. The pressure ratio of the free-jet diffuser governed the over-all operating pressure ratio of the recombined flow through the free-jet diffuser and engine for the configurations investigated and remained independent of supercritical engine pressure recovery. Increasing the amount of high-kinetic-energy air passing around the engine and through the free-jet diffuser decreased the starting and operating pressure ratios for the system regardless of whether the flow diversion was accomplished by decreasing the engine size or by increasing the engine-inlet flow spillage. In the case of the normal-shock inlet, however, steady-state flow spillage reduced only the operating pressure ratio.

2. The over-all pressure ratio required to establish supersonic flow from the nozzle was generally greater than that required to maintain operation. However, for a ratio of free-jet-nozzle to engine-inlet area of 1.35, an increase in over-all pressure ratio over the minimum for starting was necessary to maintain undisturbed stream flow into the inlet.

3. At a Mach number of 2.98, a ratio of free-jet-nozzle to engine-inlet area of 1.85, and with the engine inlet in the plane of the jet-nozzle exit, a minimum over-all pressure ratio of 5.5 was sufficient to maintain suitable engine experimental conditions. 2398

4. With a normal-shock engine inlet a range of steady subcritical inlet operation was possible, the exact mass flow which could be spilled depending on the particular installation. With a 40° cone inlet, the range of stable subcritical operation was slight and unsteady subcritical operation did not yield reliable quantitative measurements except, perhaps, for the value of engine mass-flow ratio at which "buzz" began.

5. It was possible to allow the free-jet plenum pressure to increase considerably above the static pressure of the nozzle flow without influencing conditions at the engine inlet when the engine inlet was forward of the Mach line from the lip of the jet nozzle. However, it was not possible to increase the plenum pressure to the theoretical values expected from a simple two-dimensional oblique-shock analysis.

6. At the Reynolds number of the investigation, a ratio of free-jet-nozzle to engine-inlet area of 1.35 was considered the smallest feasible, because the engine-inlet lip was at the edge of the nozzle boundary layer.

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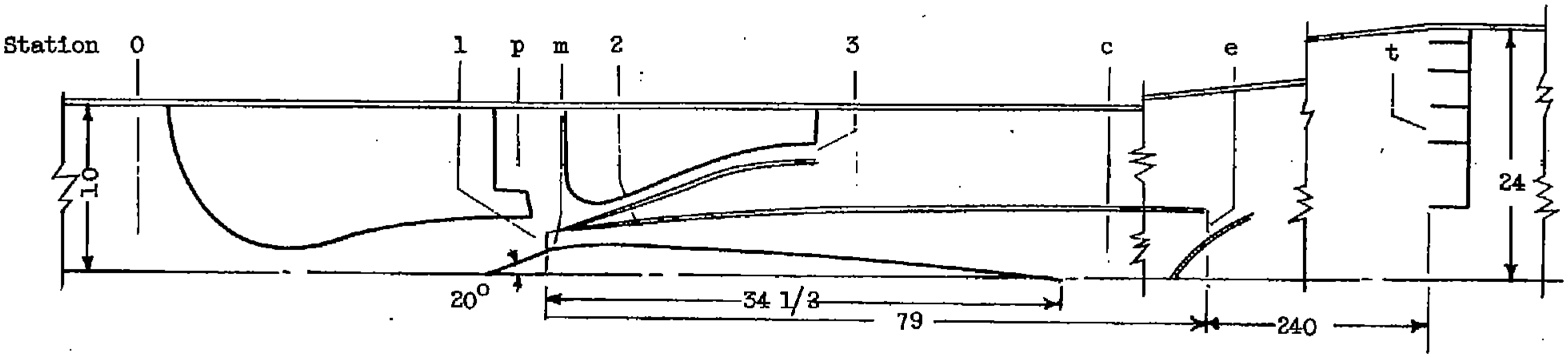


Figure 1. - Schematic diagram of three-dimensional test facility with station locations indicated (all dimensions in inches). No scale.

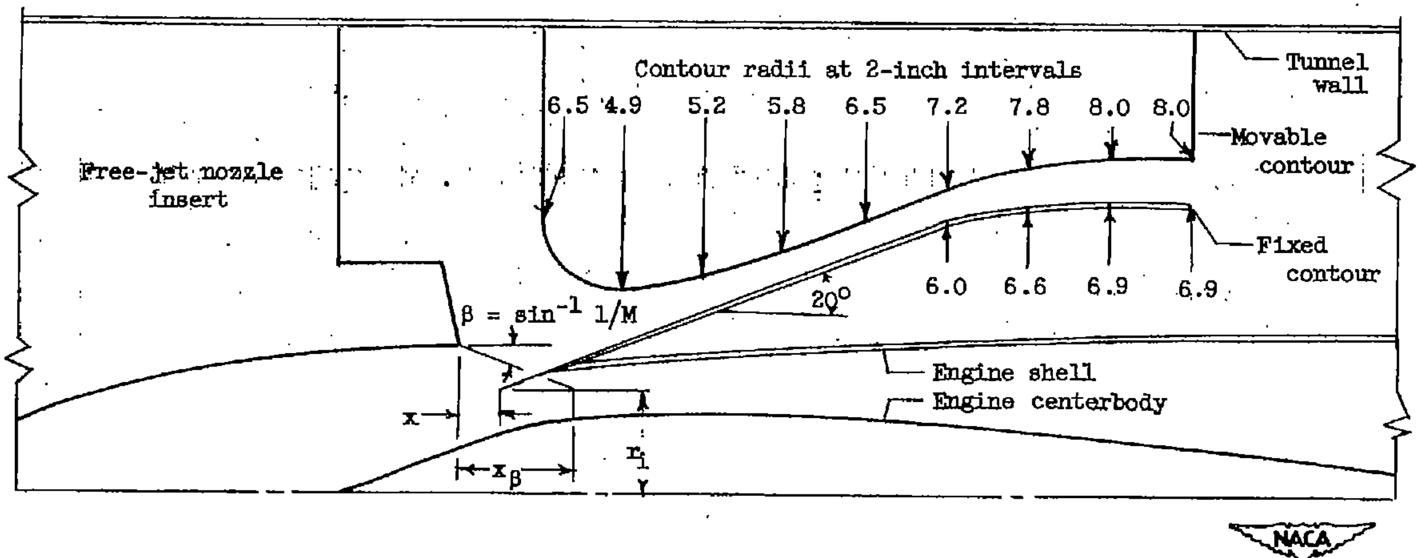


Figure 2. - Scale diagram of diffuser contour, one-fourth size.

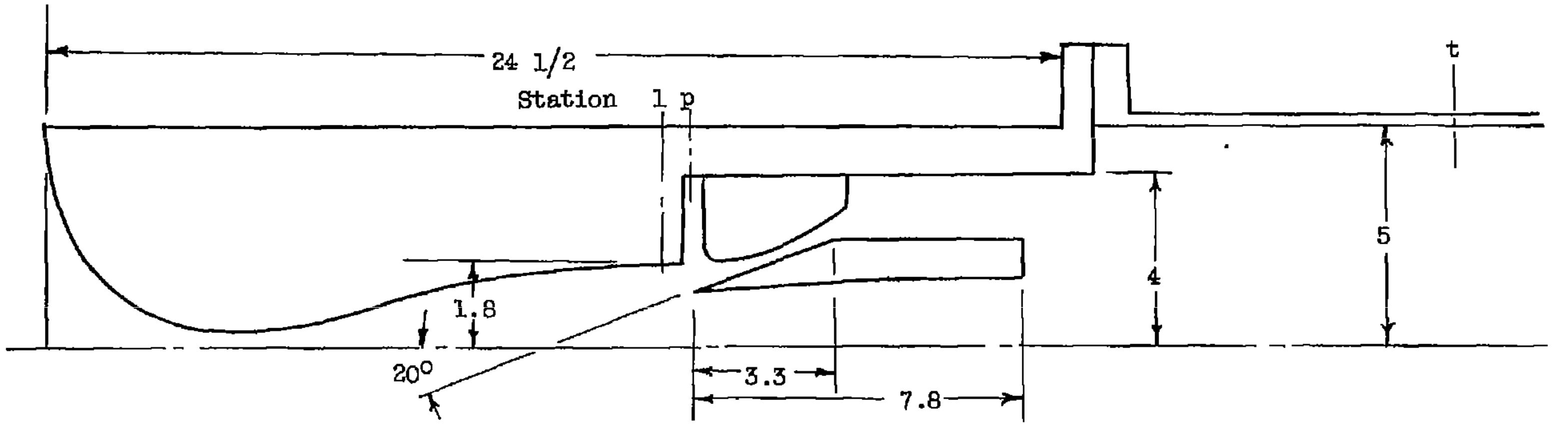
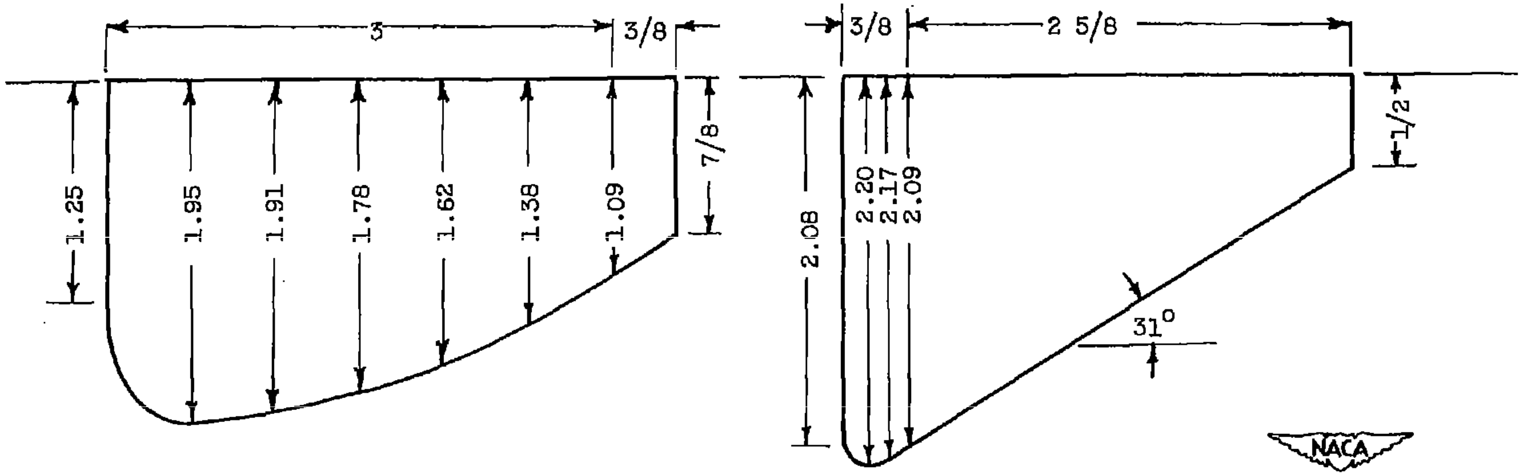


Figure 3. - Schematic diagram of two-dimensional test facility (all dimensions in inches).



(a) Diffuser contour A.

(b) Diffuser contour B.

Figure 4. - Diffuser contours used in two-dimensional investigation. Full size.

2398

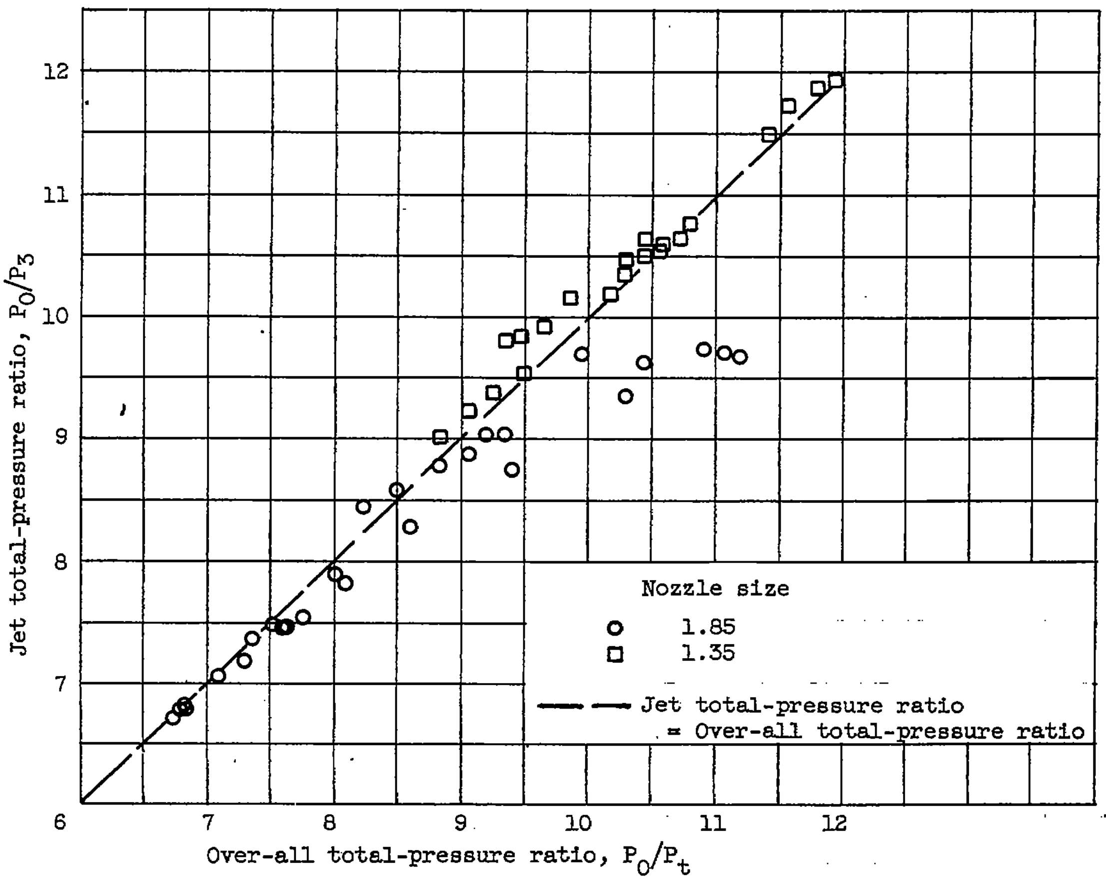


Figure 5. - Comparison of jet total-pressure ratio with over-all total-pressure ratio at Mach number 2.98.

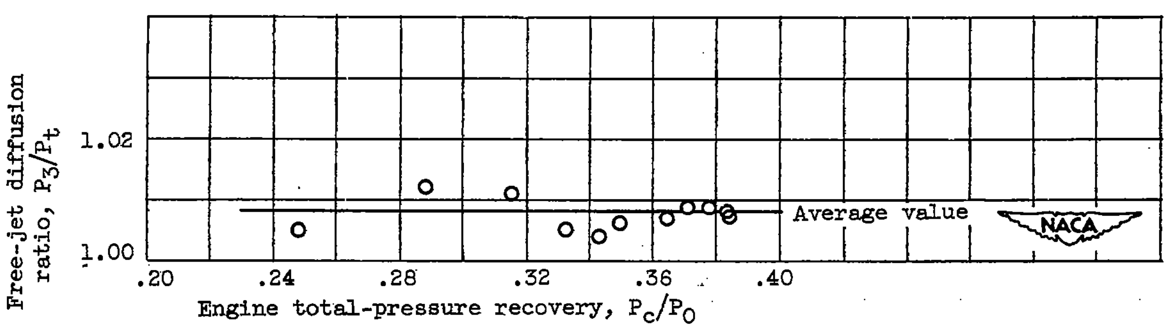
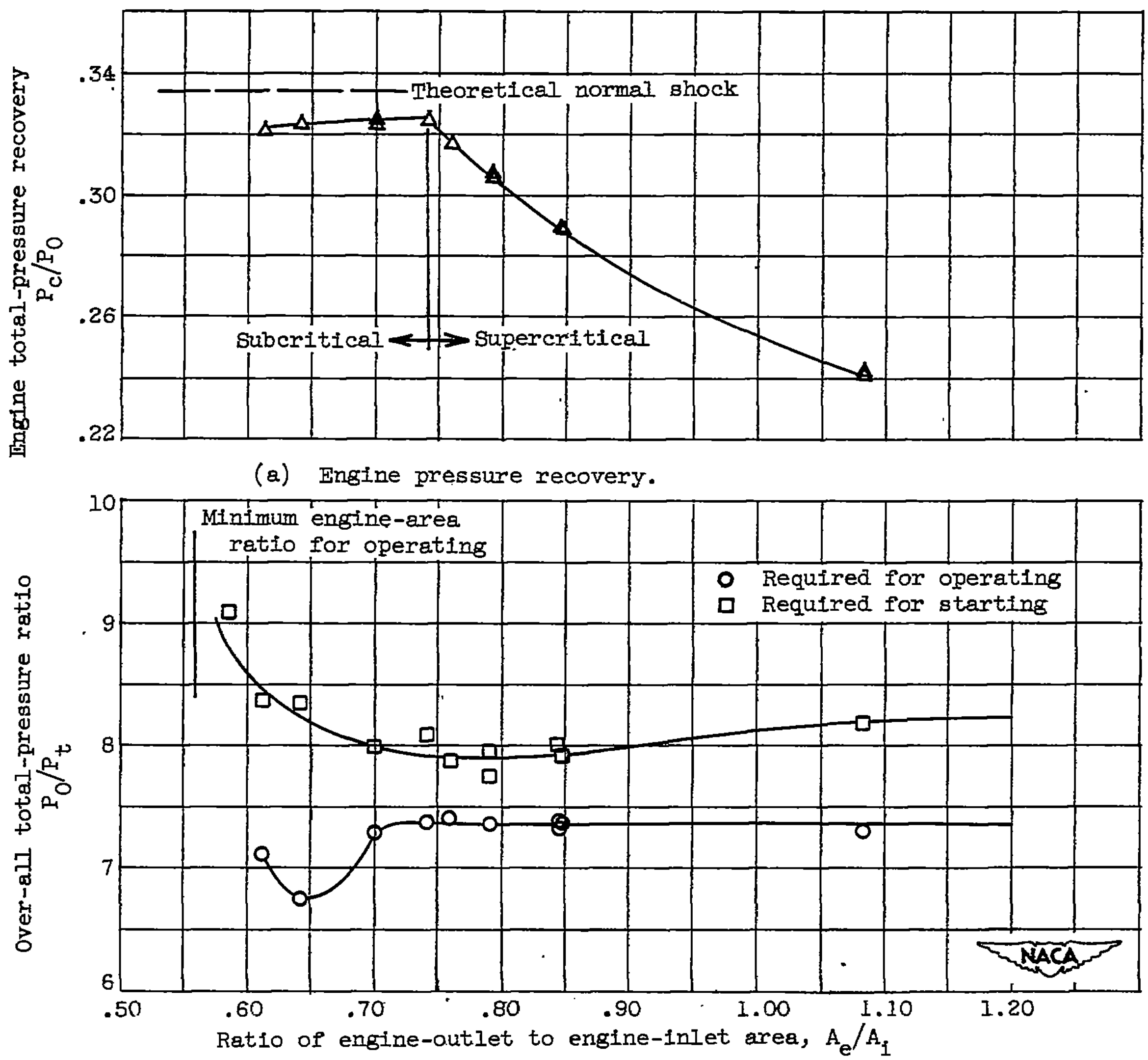


Figure 6. - Effect of supercritical engine recovery on free-jet diffusion. Mach number, 2.98; nozzle size, 1.85; over-all pressure ratio, 6.8.

2398

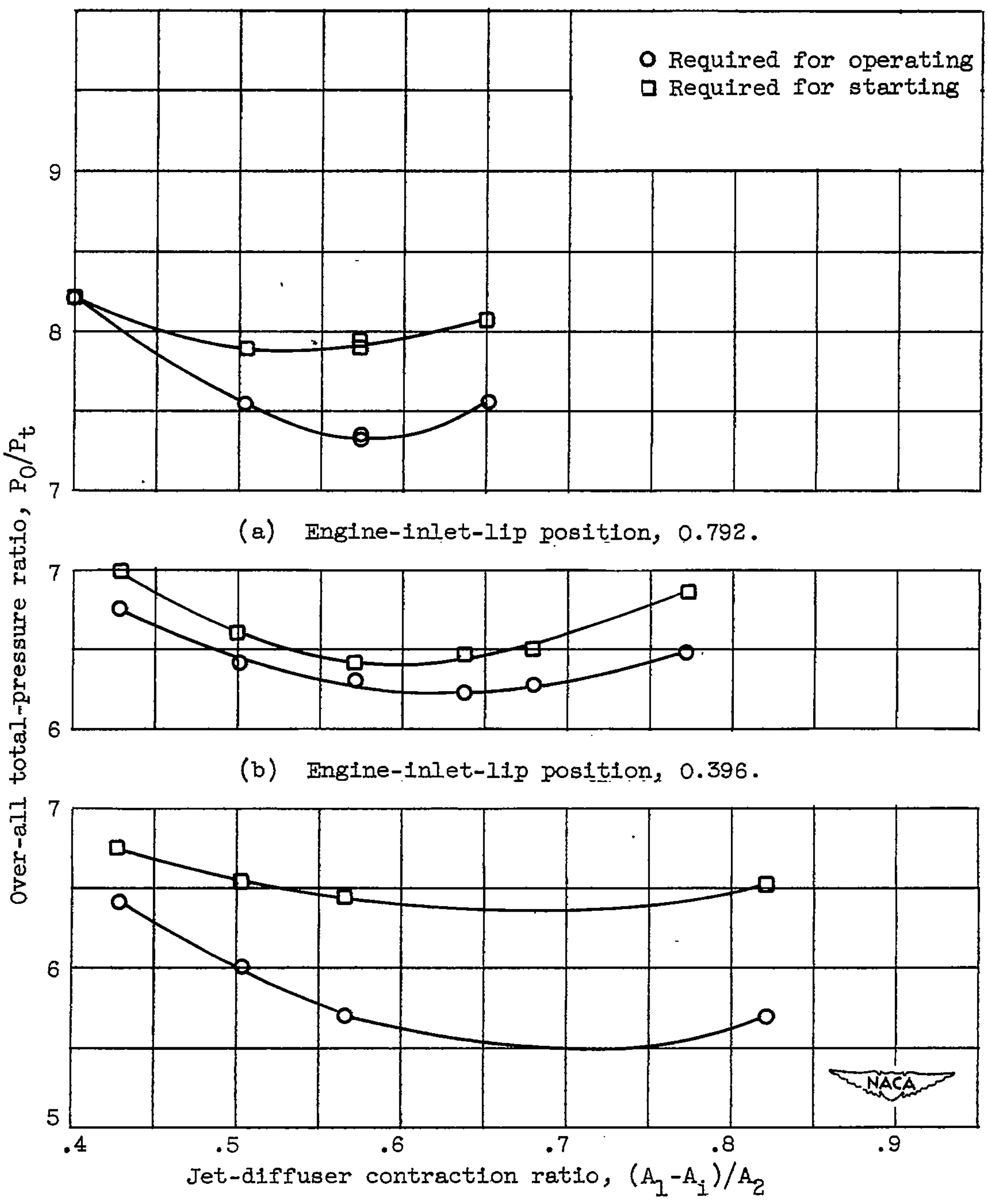


(a) Engine pressure recovery.

(b) Starting and operating pressure ratios.

Figure 7. - Effect of cold engine operating conditions on over-all starting and operating total-pressure ratios. Mach number, 2.98; nozzle size, 1.85; normal-shock inlet.

2398



(a) Engine-inlet-lip position, 0.792.

(b) Engine-inlet-lip position, 0.396.

(c) Engine-inlet-lip position, 0.

Figure 8. - Variation of required over-all starting and operating pressure ratio with jet-diffuser contraction ratio for several engine-inlet-lip positions. Mach number, 2.98; nozzle size, 1.85.

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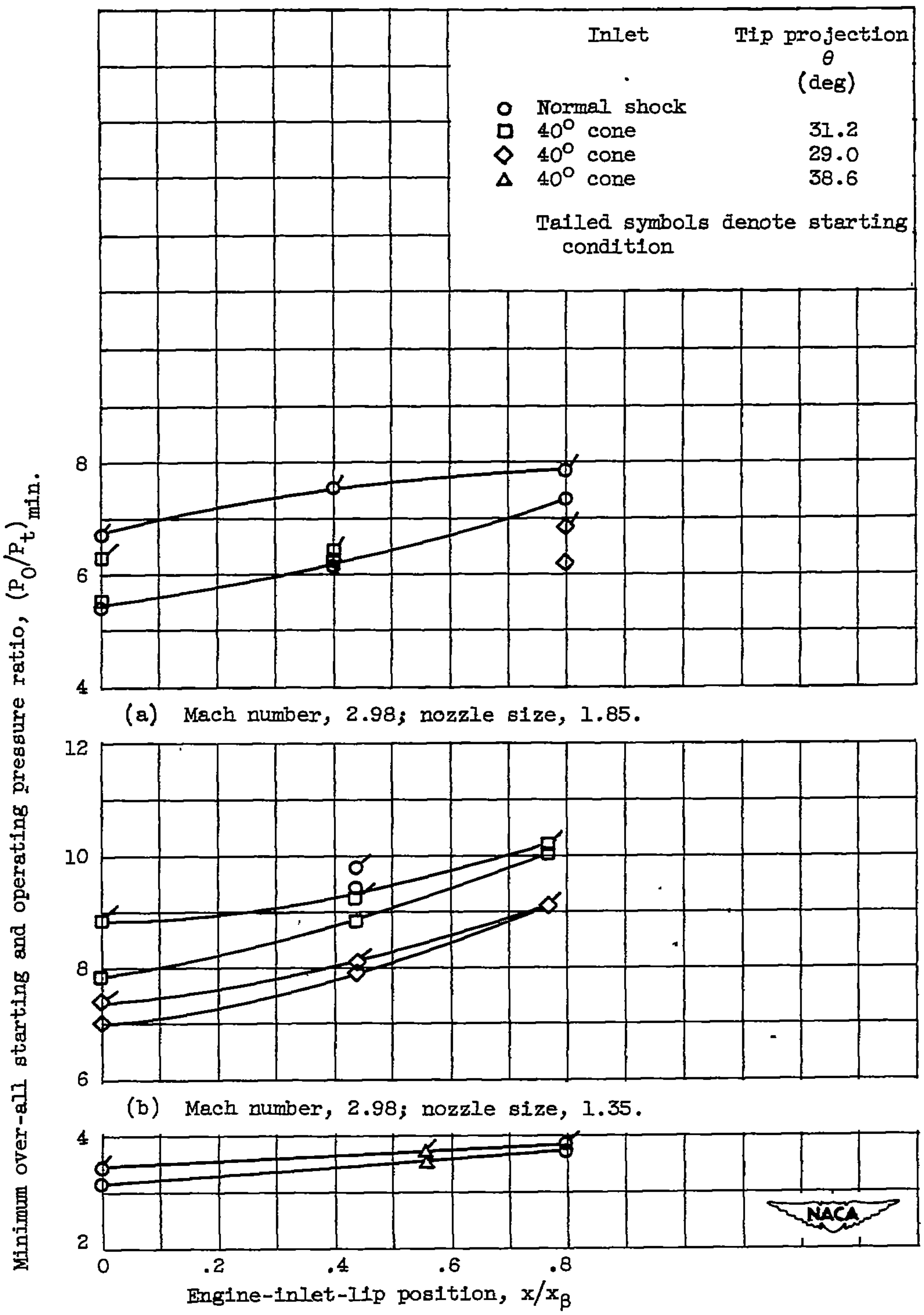

(a) Mach number, 2.98; nozzle size, 1.85.

(b) Mach number, 2.98; nozzle size, 1.35.

(c) Mach number, 2.18; nozzle size, 1.35.

Figure 9. - Minimum over-all starting and operating pressure ratios as affected by engine-inlet-lip position.

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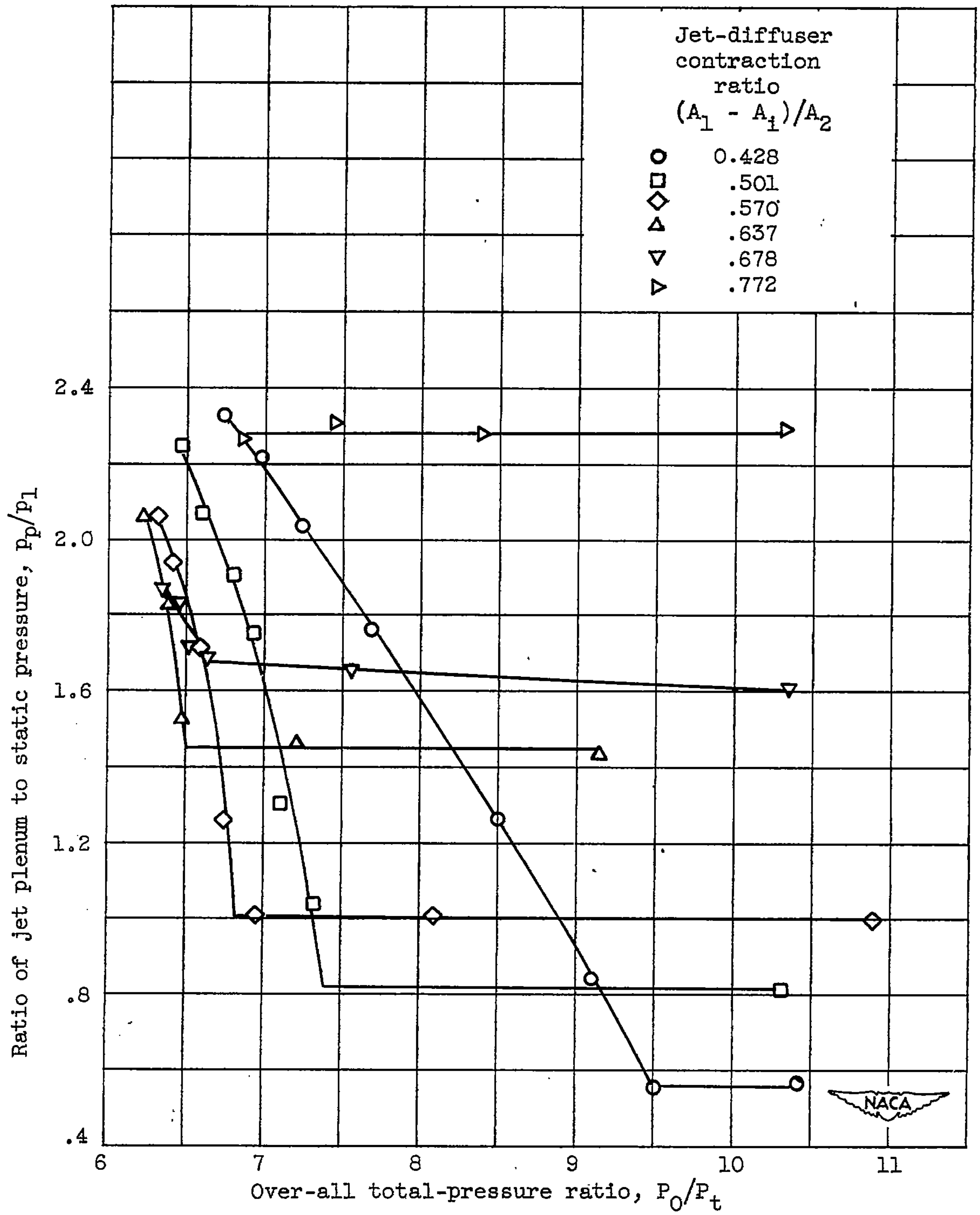
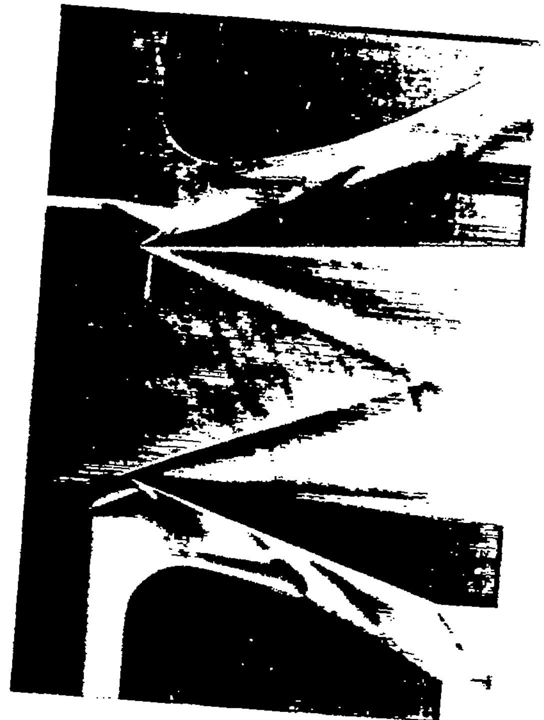


Figure 10. - Variation of ratio of jet plenum to static pressure with over-all total-pressure ratio and jet-diffuser contraction ratio. Mach number, 2.98; nozzle size, 1.85; engine-inlet-lip position, 0.396.

2398

(a) Contraction ratio, 0.795; plenum pressure, 1.408.



(b) Contraction ratio, 0.852; plenum pressure, 1.502.

(c) Contraction ratio, 0.919; plenum pressure, 1.683.

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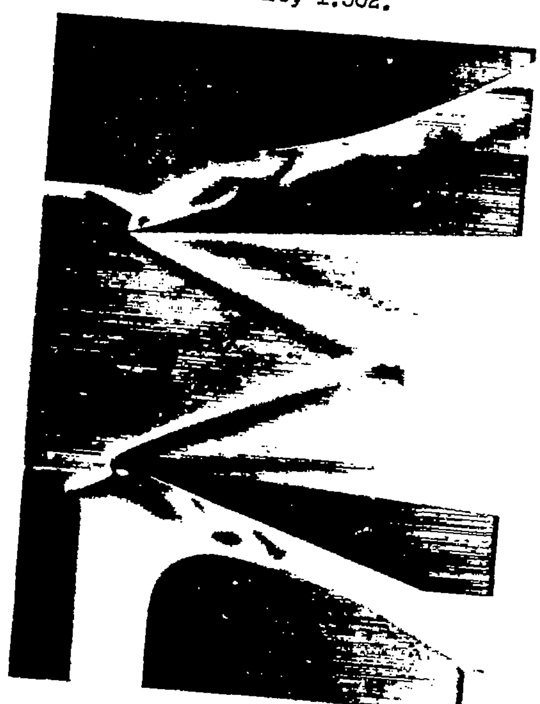
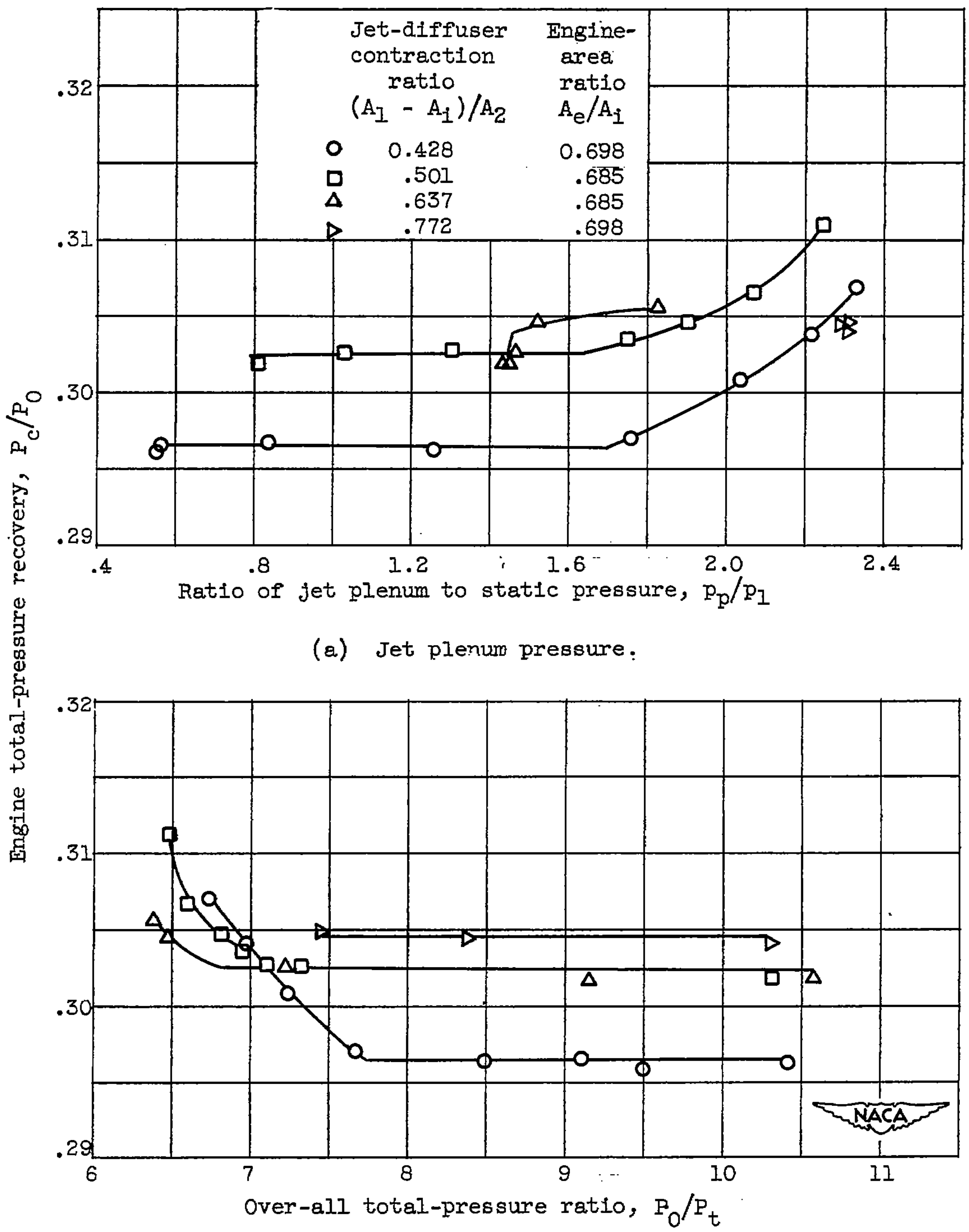


(d) Contraction ratio, 1.092; plenum pressure, 1.709.

Figure 11. - Two-dimensional flow patterns for several jet-diffuser contraction ratios. Contour A; nozzle size, 1.35; over-all total-pressure ratio, 12.2.

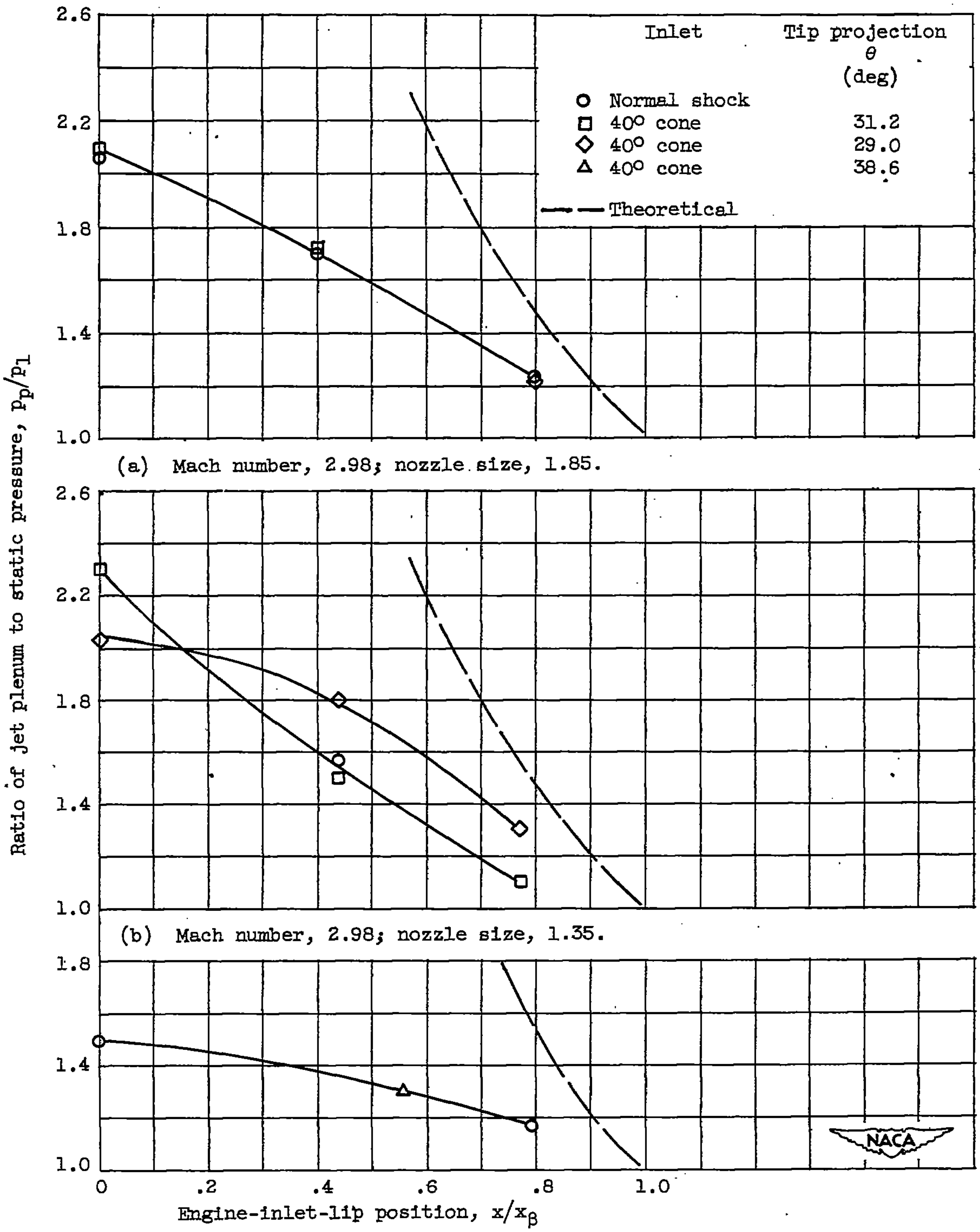
2398



(a) Jet plenum pressure.

(b) Over-all total pressure.

Figure 12. - Effect of jet-plenum pressure and over-all total pressure on engine pressure recovery. Mach number, 1.85; nozzle size, 1.85; engine-inlet-lip position, 0.396.

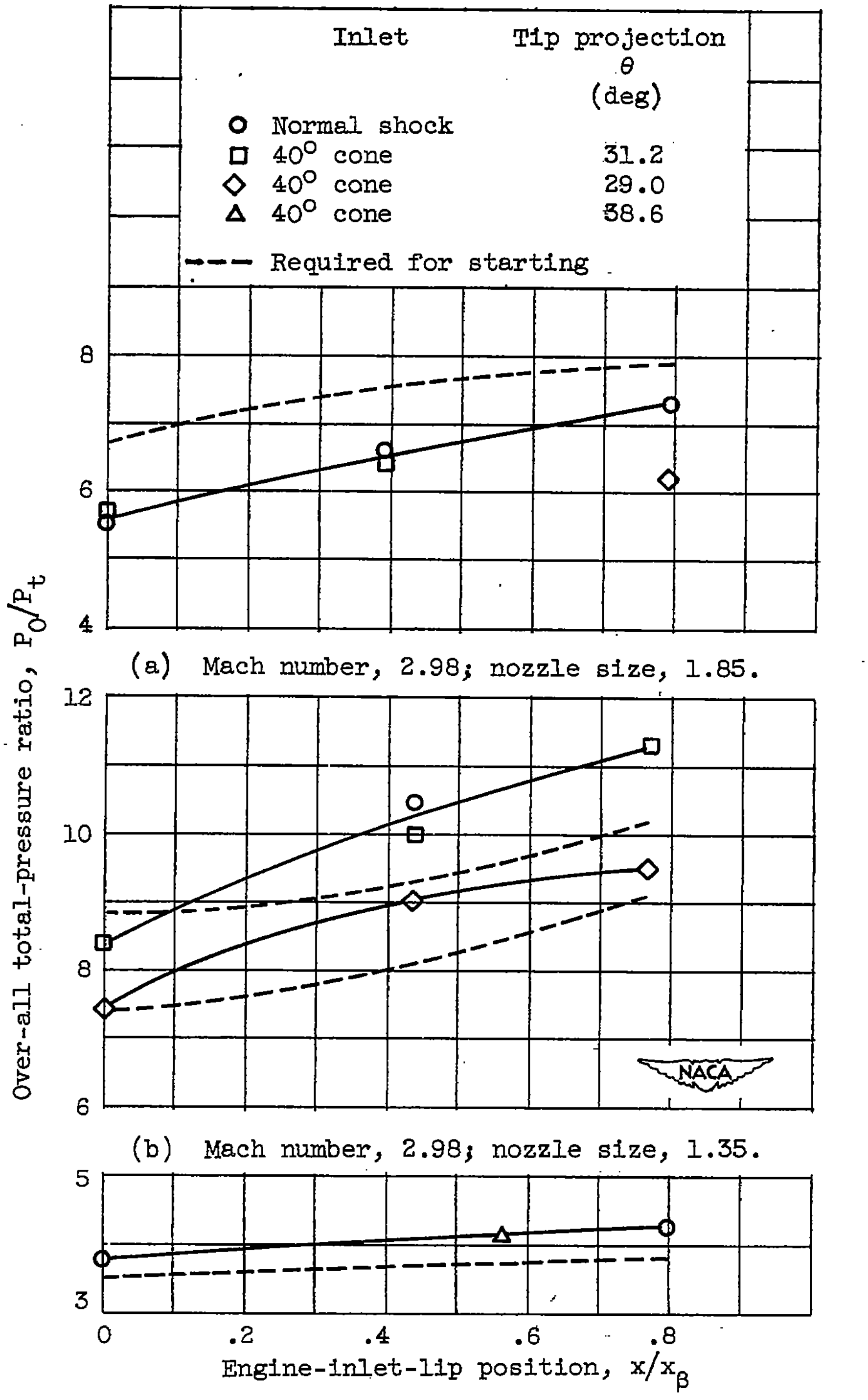


(a) Mach number, 2.98; nozzle size, 1.85.

(b) Mach number, 2.98; nozzle size, 1.35.

(c) Mach number, 2.18; nozzle size, 1.35.

Figure 13. - Maximum ratios of jet plenum to static pressures for shock-free flow into engine inlet.

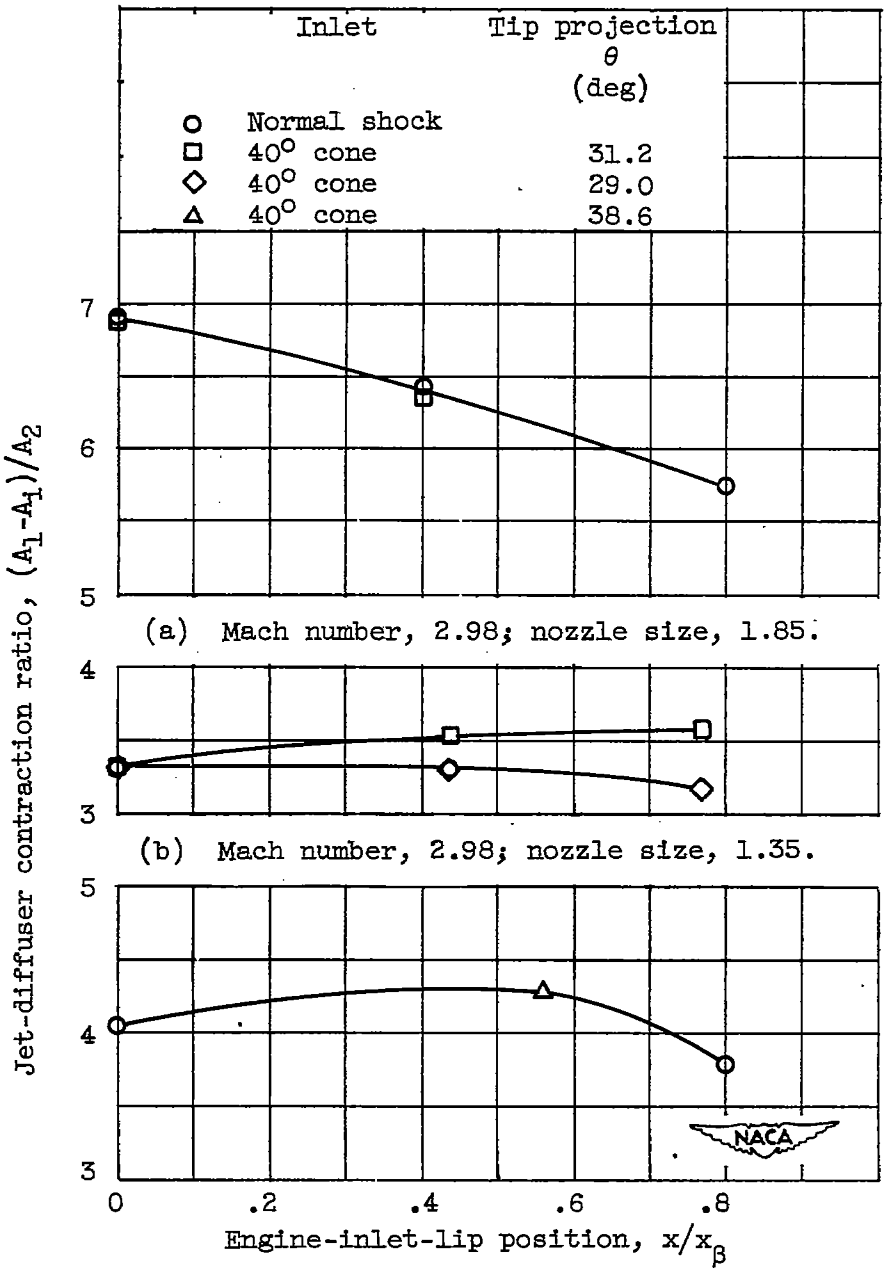


(a) Mach number, 2.98; nozzle size, 1.85.

(b) Mach number, 2.98; nozzle size, 1.35.

(c) Mach number, 2.18; nozzle size, 1.35.

Figure 14. - Required over-all total-pressure ratios for shock-free flow into engine inlet.



(a) Mach number, 2.98; nozzle size, 1.85.

(b) Mach number, 2.98; nozzle size, 1.35.

(c) Mach number, 2.18; nozzle size, 1.35.

Figure 15. - Optimum jet-diffuser contraction ratio.

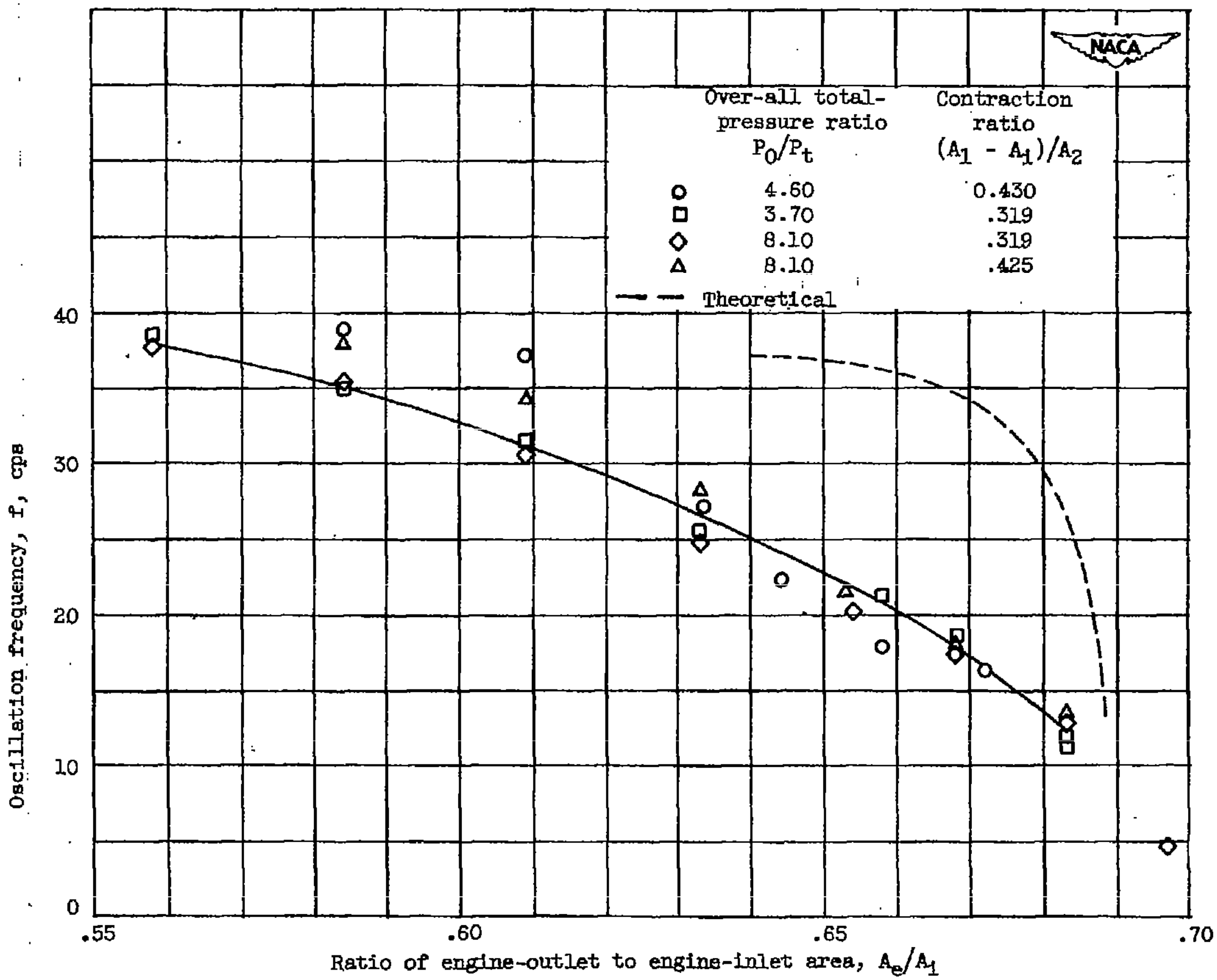
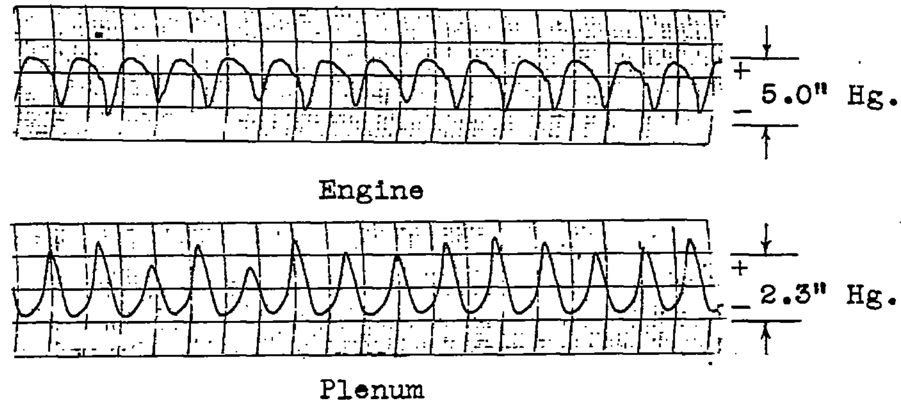
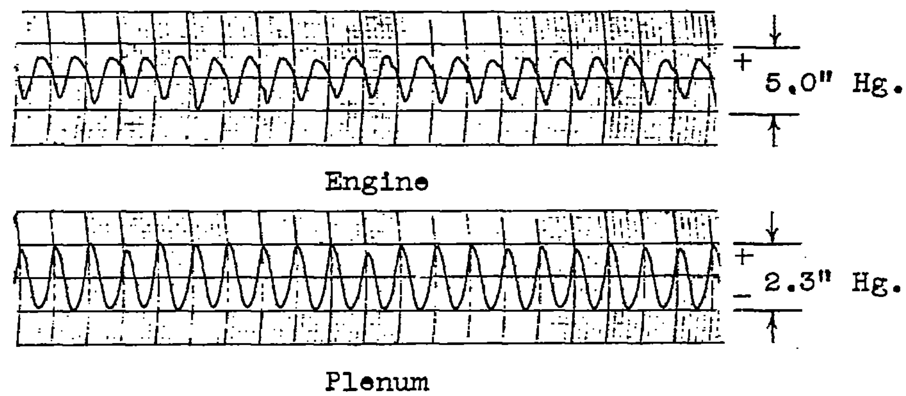


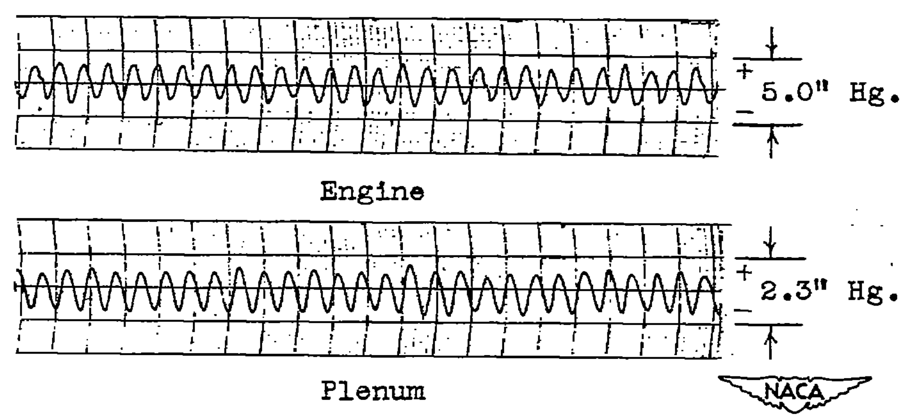
Figure 16. - Engine combustion-chamber-pressure oscillation for subcritical inlet flow. Mach number, 2.18; nozzle size, 1.35; engine-inlet-lip position, 0.557.



(a) Ratio of engine-outlet to engine-inlet area, 0.668.



(b) Ratio of engine-outlet to engine-inlet area, 0.633.



(c) Ratio of engine-outlet to engine-inlet area, 0.584.

Figure 17. - Engine combustion-chamber and jet-plenum pressure fluctuation for subcritical engine-inlet flow. Mach number, 2.18; nozzle size, 1.35; engine-inlet-lip position, 0.557.

[redacted]

(a) Over-all total-pressure ratio, 13.8; plenum pressure, 0.90.

(b) Over-all total-pressure ratio, 8.06; plenum pressure, 0.90.

(c) Over-all total-pressure ratio, 7.56; plenum pressure, 1.00.

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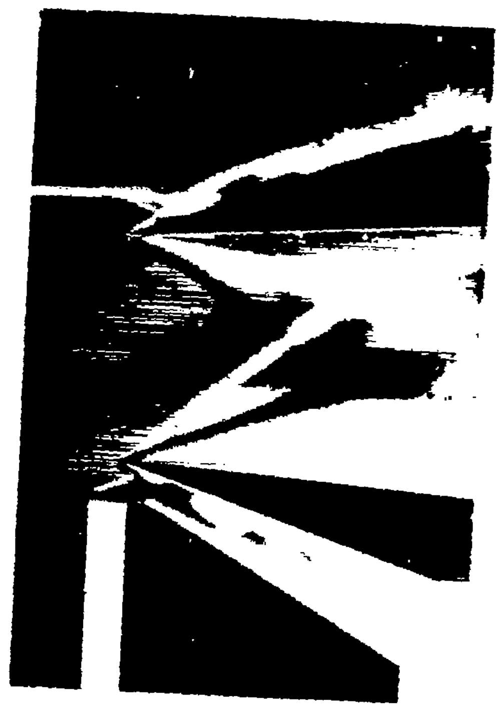

(d) Over-all total-pressure ratio, 7.22; plenum pressure, 1.19.

Figure 18. - Two-dimensional flow patterns for several over-all total-pressure ratios. Contour B; nozzle size, 1.35; contraction ratio, 1.239.

[redacted]